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OPTICAL MEASUREMENTS OF NO AND NO_2 IN THE EXHAUST OF AN F101-GE-100 ENGINE AT SIMULATED ALTITUDES

J. D. Few
ARO, Inc., a Sverdrup Corporation Company

ENGINE TEST FACILITY
ARNOLD ENGINEERING DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
ARNOLD AIR FORCE STATION, TENNESSEE 37389

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Eules L. Hively

EULES L. HIVELY
Project Manager, Research Division
Directorate of Test Engineering

Approved for publication:

FOR THE COMMANDER

Marion L. Laster

MARION L. LASTER
Director of Test Engineering
Deputy for Operations

ERRATA

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(UNCLASSIFIED REPORT)

OPTICAL MEASUREMENTS OF NO AND NO_2 IN THE EXHAUST OF AN F101-GE-100 ENGINE AT SIMULATED ALTITUDES

J. D. Few, ARO, Inc.

Arnold Engineering Development Center
Air Force Systems Command
Arnold Air Force Station, Tennessee 37389

Errors have been found in the theoretical model used to obtain the data presented in Figs. 10 through 12; consequently, they must be considered suspect.

An AEDC Technical Report containing the correct model and corrected data will be issued.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Measurements of nitric oxide (NO) and nitrogen dioxide (NO_2) concentrations were made in the exhaust of an F101-GE-100 engine using ultraviolet (UV) spectral absorption techniques. The measurements were made at a station 10.2 cm downstream of the engine nozzle exit. The NO measurements were made at two engine power settings, intermediate and maximum afterburning; the NO_2 measurement was made only at intermediate power. The line-of-

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20. ABSTRACT (Continued)

sight absorption measurements through the axisymmetric exhaust stream were converted to local values of concentration via an iterative radial inversion computation. These in situ measurements are compared to NO_x concentration values obtained by conventional probe sampling techniques using a chemiluminescent analyzer.

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PREFACE

The work reported herein was conducted by the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), under Program Element 65807F. The results of the test were obtained by ARO, Inc., AEDC Division (a Sverdrup Corporation Company), operating contractor for the AEDC, AFSC, Arnold Air Force Station, Tennessee, under ARO Project Numbers R32P-A6A and R32P-C6A. The project was under the direction of E. L. Hively, AEDC/DOTR. The manuscript (ARO Control No. ARO-ETF-TR-77-42) was submitted for publication on June 6, 1977.

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1.0 INTRODUCTION

The research reported herein is part of a continuing program at the Arnold Engineering Development Center (AEDC) to assess the feasibility of employing optical techniques for the measurement of pollutant emissions in jet engine exhaust gases. This report describes the application of a previously developed ultraviolet (UV) resonance absorption technique (Refs. 1, 2, and 3) for the measurement of nitric oxide (NO) and a continuum absorption technique for the measurement of nitrogen dioxide (NO_2) in the exhaust of an F101-GE-100 engine operated at simulated flight conditions.

The measurements were made to extend the knowledge of NO and NO_2 concentration levels in a modern jet engine. This was the first attempt at an in situ measurement of NO_2 in a jet engine exhaust at AEDC and is of major importance in the overall program of pollution measurements.

The investigation described here was similar to an unpublished program conducted at AEDC in early 1975 by B. M. Bishop and D. L. Davidson, AEDC, to measure exhaust emissions using conventional sampling probes with process gas type instruments. The probe-measured profiles of the total oxides of nitrogen (NO_x) concentration used in this report were obtained from the earlier program. The optical measurements were obtained from engine S/N 470006/8, an Interim Product Verification Status engine, and the probe data were obtained from engine S/N 470011/4, a Preflight Rating Test Status engine. The engine cycle performances on these two engines were similar; therefore, a comparison of the species concentration measurements by the two techniques, optical and probe, is reasonable.

The measured values of NO_x obtained using the probe method are compared to the NO values obtained using the optical method on a point-by-point basis along the radius of the jet engine exhaust system. The

optical NO_2 measurement method employed produced only an upper limit of approximately 20 ppmv, thus indicating that the majority of the NO_x measured occurs as NO at the measurement positions employed in this study. The probe data were obtained at intermediate power only; therefore, only one profile can be presented for comparison between the probe and optical measurements.

2.0 DESCRIPTION OF APPARATUS

2.1 ENGINE AND TEST FACILITY

The F101-GE-100 engine is a mixed-flow, augmented turbofan with a converging-diverging exhaust nozzle. A detailed description of the engine is presented in Ref. 4.

The characteristics of the Propulsion Development Test Cell (J-2) are described in Ref. 5. The engine installation was of the direct-connect type, in which ram air is supplied to the engine inlet at the temperature and pressure corresponding to a given air speed and altitude, and the static pressure at the engine exit is maintained at the pressure corresponding to the given altitude. The engine could be operated at any power setting; however, spectral absorption data were taken only at intermediate and maximum afterburn power settings. The engine and the spectral absorption apparatus installation in the J-2 test cell are shown schematically in Fig. 1 and photographically in Fig. 2.

2.2 UV RESONANCE ABSORPTION SYSTEM

The in situ resonance absorption system, located as shown in Fig. 1, consisted of a resonance lamp source with transmitting optics and a 0.5-m spectrometer with receiving optics located on opposite sides of the engine exhaust nozzle on arms of a traversing mechanism which was used to scan the exhaust stream. The source optical system provided a

1-cm-diam parallel beam across the exhaust. The radiation source was a capillary high voltage (3,000 vdc) discharge tube through which a 12:3:1 mixture (by volume) of argon, nitrogen, and oxygen, respectively, flowed at a pressure of 0.8 kPa. The discharge tube was water cooled to lower the temperature of the gas mixture, thus ensuring a narrow line NO radiation source.

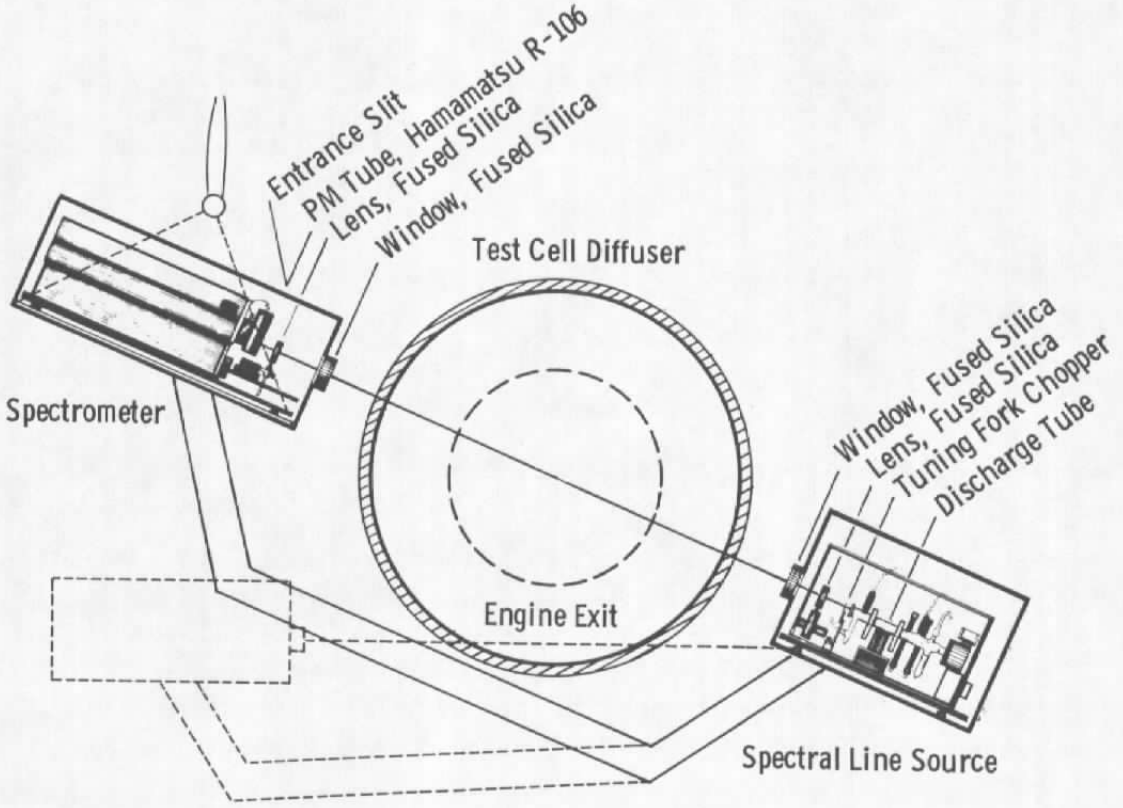

Figure 1. Diagram of installation of spectral absorption apparatus in Propulsion Development Test Cell (J-2) for NO and NO_2 concentration measurements in exhaust of F101 engine.

The spectrometer (receiver) used in this experiment was a 0.5-m, Czerny-Turner type mount, grating instrument with a 2,360 groove/mm grating blazed for maximum reflection at 3,000 Å. The spectrometer was equipped with 200-m curved slits, resulting in a 1.6-Å spectral bandpass. An RCA 1P28 photomultiplier tube, selected for low noise and high gain, was used as a detector. The photomultiplier tube signal was amplified by an operational amplifier, and the signal was recorded as the ordinate on an x-y plotter.

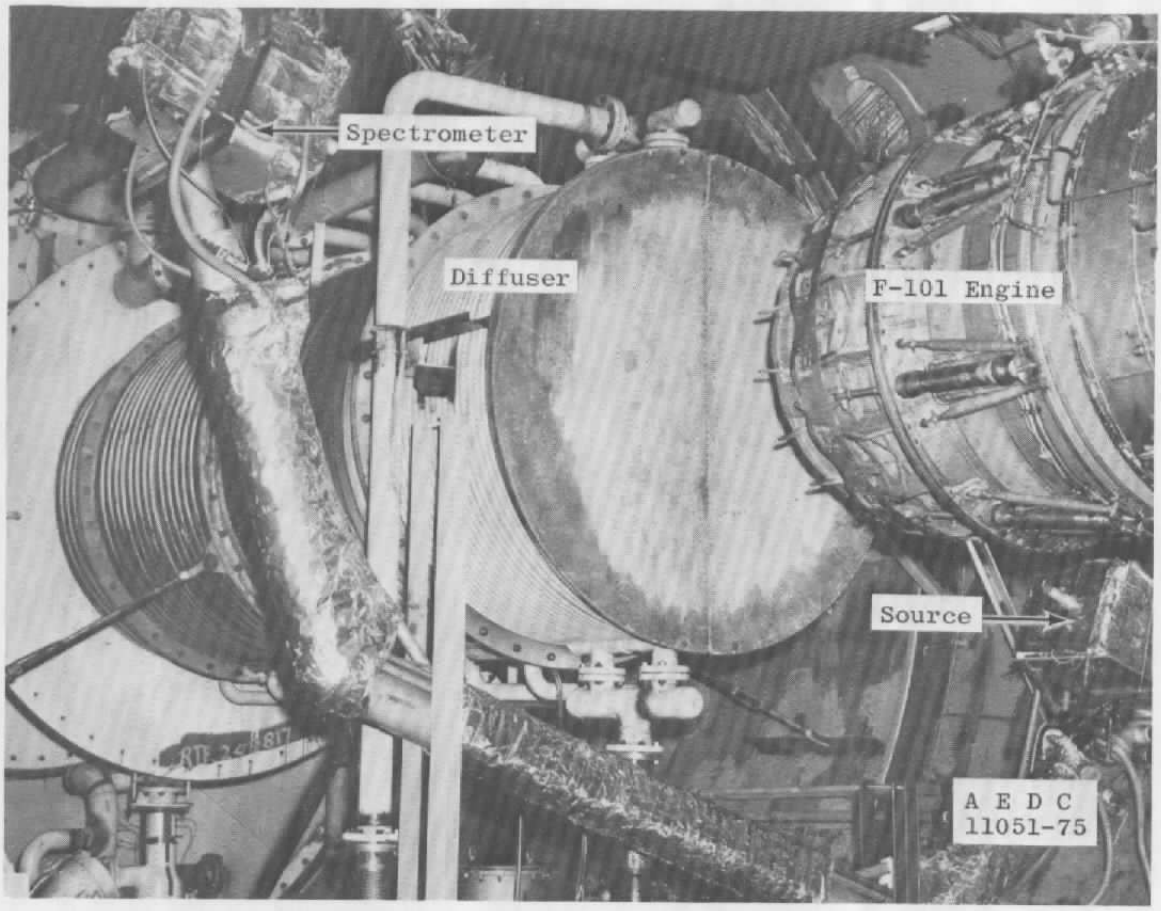

Figure 2. Photograph of installation of spectral absorption apparatus in Propulsion Development Test Cell (J-2) for NO and NO_2 concentration measurements in exhaust of F101 engine.

The conventional wavelength drive of the spectrometer was replaced by a Selsyn motor receiver which could be driven by a Selsyn driver located in the control room in order to provide remote control of the wavelength. A 10-turn potentiometer was geared to the Selsyn receiver shaft and provided the wavelength signal which was recorded as the absicissa on the x-y plotter.

2.3 CONTINUUM ABSORPTION SYSTEM

The continuum absorption system employed for the measurement of NO_2 was mounted on the traversing mechanism described in Section 2.2.

The 0.-5m spectrometer and associated electronics were also used as described in Section 2.2. The NO narrow line source was replaced with a tungsten halogen lamp which provided an intense irradiation source over the spectral range of interest. The spectrometer scan mechanism was remotely operated to accomplish the absorption measurement at preselected wavelength intervals of 2,300 to 2,500 Å and 4,000 to 5,000 Å in order to acquire the necessary optical absorption data for determining NO_2 species concentration. The traversing yoke was positioned to afford the maximum optical path for the absorption measurement and thus the maximum sensitivity of signal. No attempt was made to do a spatial scan of the exhaust plume.

3.0 APPLICATION OF METHODS

3.1 RESONANCE ABSORPTION METHOD (NO)

The resonance absorption technique for the measurement of species concentrations involves the relationship between the transmissivity at some wavelength and the properties of the gas (species number density, temperature, and pressure) in the absorbing path.

For the case of cylindrical symmetry, an inversion procedure (outlined in Ref. 6) can be applied when the transmissivity distribution has been measured, $\tau(y)$, and the static temperature, $T(r)$, and the static pressure, $P(r)$, are known. The procedure requires the assumption of constant properties in concentric zones of the jet engine exhaust. Measurements of transmission were made through chords of the exhaust gas stream as shown in Fig. 3. The inversion procedure starts at the outside zone (which is determinate, since it is homogeneous) and proceeds inward with an iteration of the inner, unknown number densities (N) to reproduce the measured transmissivities, $\tau(y)$. In this way the number density as a function of the radial position was determined. The detailed inversion and data reduction scheme has been documented elsewhere (Ref. 6).

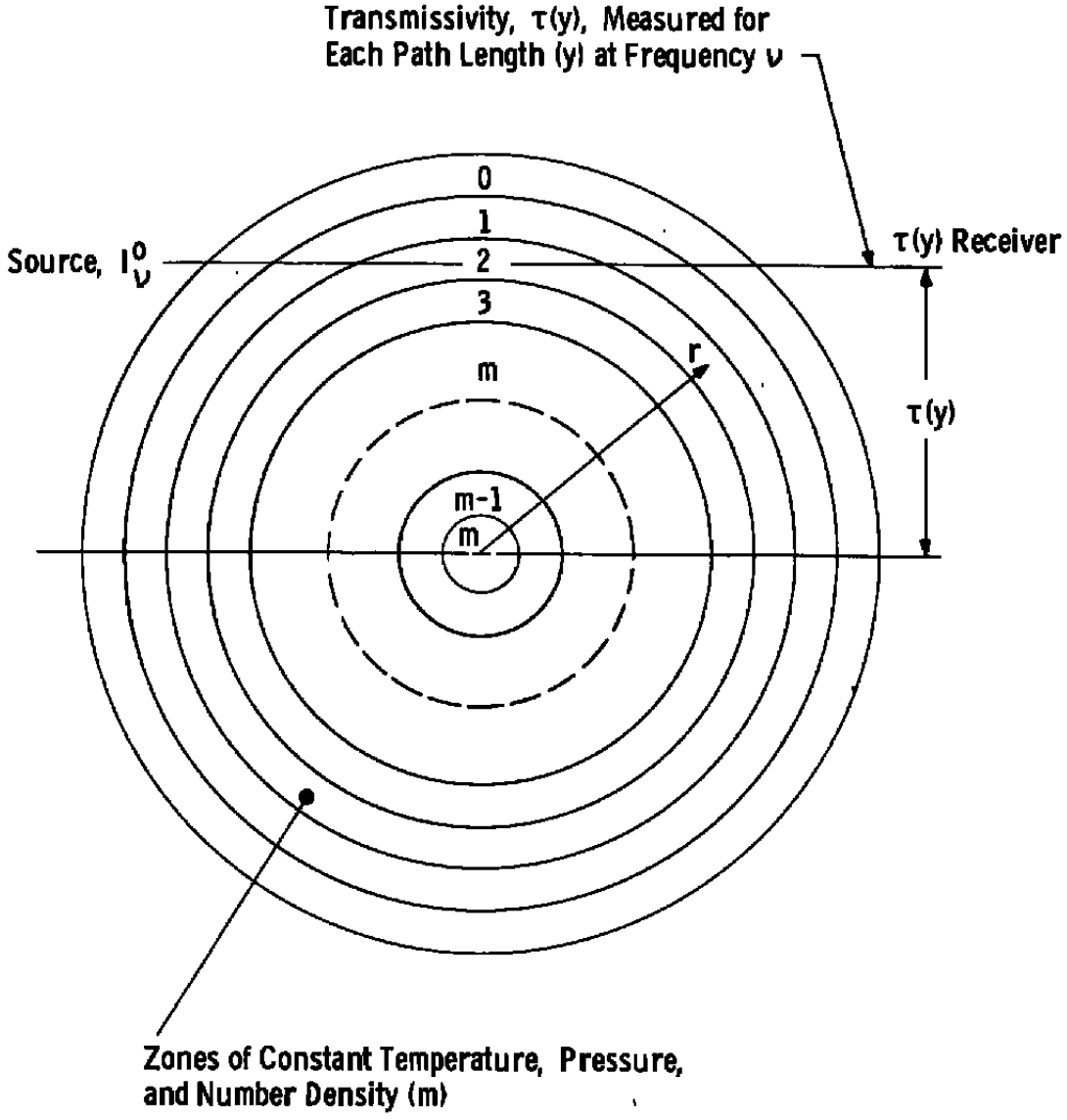

Figure 3. Illustration of radial inversion problem for determination of local concentration from transmissivity measurements.

The radial static temperature distributions (Figs. 4 and 5) for both engine power settings and the static pressure distribution for the afterburning power setting were obtained from the engine manufacturer. The exhaust stream radial static pressure distribution was assumed constant and equal to the cell pressure at the intermediate power setting.

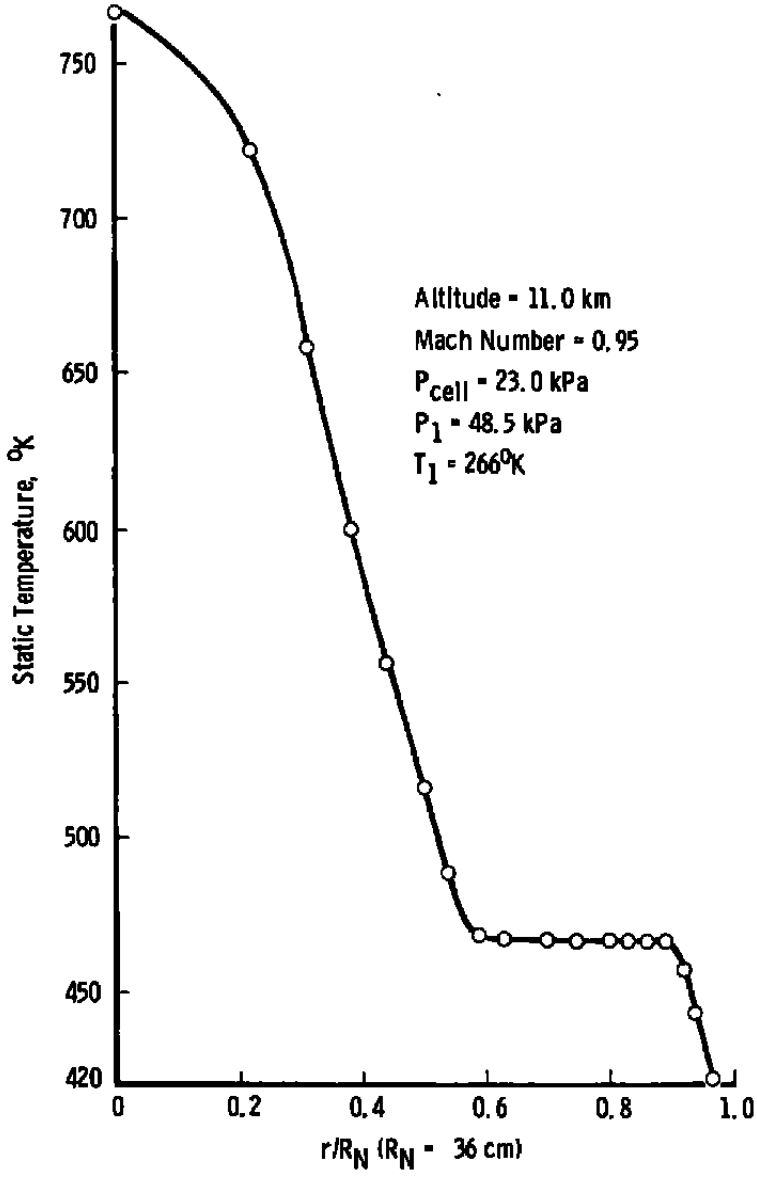

Figure 4. Static temperature profile at nozzle exit for intermediate power.

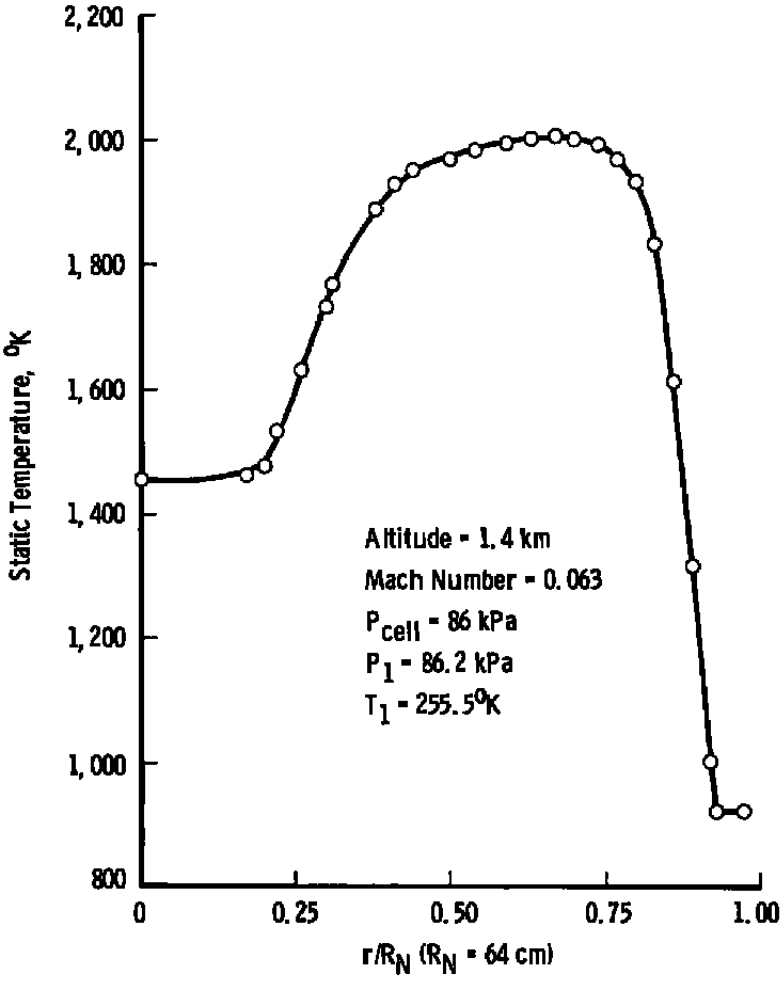

Figure 5. Static temperature profile at nozzle exit for maximum afterburn power.

3.2 CONTINUUM ABSORPTION METHOD (NO_2)

A continuum absorption technique was used for the measurement of NO_2 concentration in the jet engine exhaust. The continuum radiation was directed through the centerline of the jet engine exhaust (maximum optical path length) to the spectrometer (receiver), which was scanned through the desired wavelength range to acquire the absorption measurement.

The NO_2 system was calibrated in the laboratory using an absorption cell of known length in which the pressure and temperature could be

controlled. The absorption spectra obtained in the laboratory at several different partial pressures of NO_2 served as a calibration for the measurement of NO_2 in the jet engine exhaust.

4.0 RESULTS AND DISCUSSION

4.1 SAMPLING PROBE DATA

Gas sample probe data were obtained at several flight conditions at the intermediate engine power setting. The probe data used in this report for comparison with the optical measurement will be the total oxides of nitrogen (NO_x) since only total oxides of nitrogen were measured.

The radial profiles (obtained by Bishio and Davidson; see Section 1.0) were made using the gas sample probe at a station 10.2 cm downstream of the engine nozzle exit, which coincides with the location of the optical apparatus. The optical and probe data were not taken at the same altitude; however, the probe data were taken at altitudes which enveloped the optical data acquisition point as shown in Fig. 6.

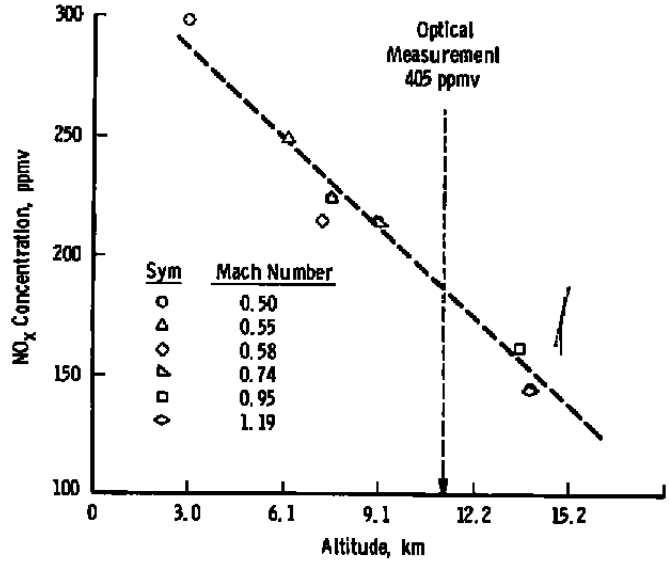

Figure 6. Results of probe-measured values of NO concentration versus altitude at centerline of jet engine exhaust at intermediate power.

4.2 UV RESONANCE ABSORPTION DATA (NO)

The UV optical system was used to obtain data for the two simulated flight conditions listed in Table 1. Spatial scans of the (2,2) bandhead of NO were also obtained in order to correct for extraneous absorption (window fogging, particulate scattering, etc.). A spectral scan taken at the centerline of the exhaust stream during afterburning is shown in Fig. 7.

The data reduction is accomplished as outlined in Ref. 6. The results of the data reduction procedure yield the (corrected) transmissivity of the (0,0) γ-band for that line of sight. The measurement is repeated through several chords, and the data are then inverted as discussed previously to obtain the radial profile of NO concentration. The transmissivity data are shown in Figs. 8 and 9 for the two flight conditions listed in Table 1. The results of inverting the transmissivity data at intermediate engine power to local values of NO concentration are given in Fig. 10. For comparison, the local values of NO_x concentration obtained from the probe sampling system are also shown in Fig. 11. The probe values of the concentration are less than the optically obtained values along the radial path from the center to 50 percent of the exhaust gas stream radius; the ratio of the two values varies from about 2.0 at the centerline to about 1.0 near the edge of the exhaust stream.

It should be noted that the temperature has decreased at 0.5 r/R_N by about 30 percent (to 465°K) of the centerline value (see Fig. 4). This is the point in the exhaust stream where the optical measurement of NO approached the probe measurement of NO_x (Fig. 11). This suggests the possibility that a temperature-dependent reaction involving NO may be occurring within the probe (Ref. 7).

Table 1. Summary of Test Conditions

Altitude, km	Mach Number	Fan Speed, rpm	Fan Air Flow, kg/sec	Fuel Flow, kg/hr	Fuel to Air Ratio	Power Level	EI^{a} NO_x	Methods of Measurement
11	0.95	7,220	72.5	2,080	0.0076	Intermediate	---	Optical
1.4	0.063	7,500	134.7	29,359	0.061	Max AB	---	Optical
7.6	0.58	7,190	80.7	2,120	0.0073	Intermediate	23.2	Probe
9.1	0.74	7,190	73.5	1,970	0.0074	Intermediate	21.4	Probe
13.7	0.95	7,210	44.9	1,243	0.0077	Intermediate	13.2	Probe

[a] Integrated Emission Index (Bishop & Davidson), kg NO_x/1,000 kg fuel

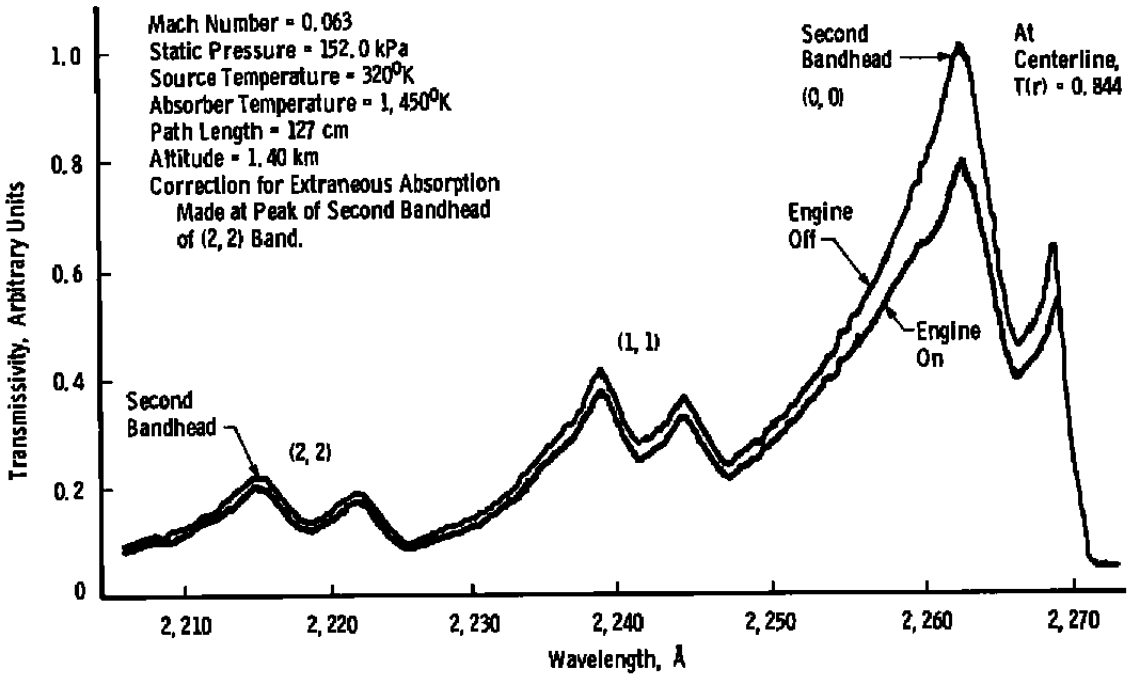

Figure 7. Measured transmission spectra of NO (0,0) γ-band at centerline 10.2 cm downstream of jet engine nozzle exit at maximum afterburner.

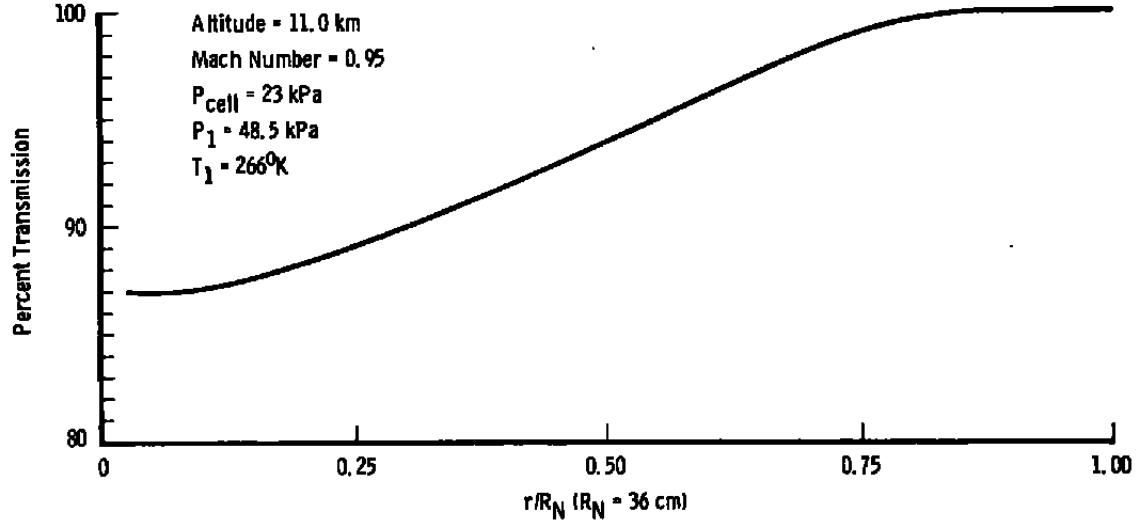

Figure 8. Measured transmission profiles using the second bandhead of the (0,0) γ-band of NO at 10.2 cm downstream of nozzle exit for intermediate power.

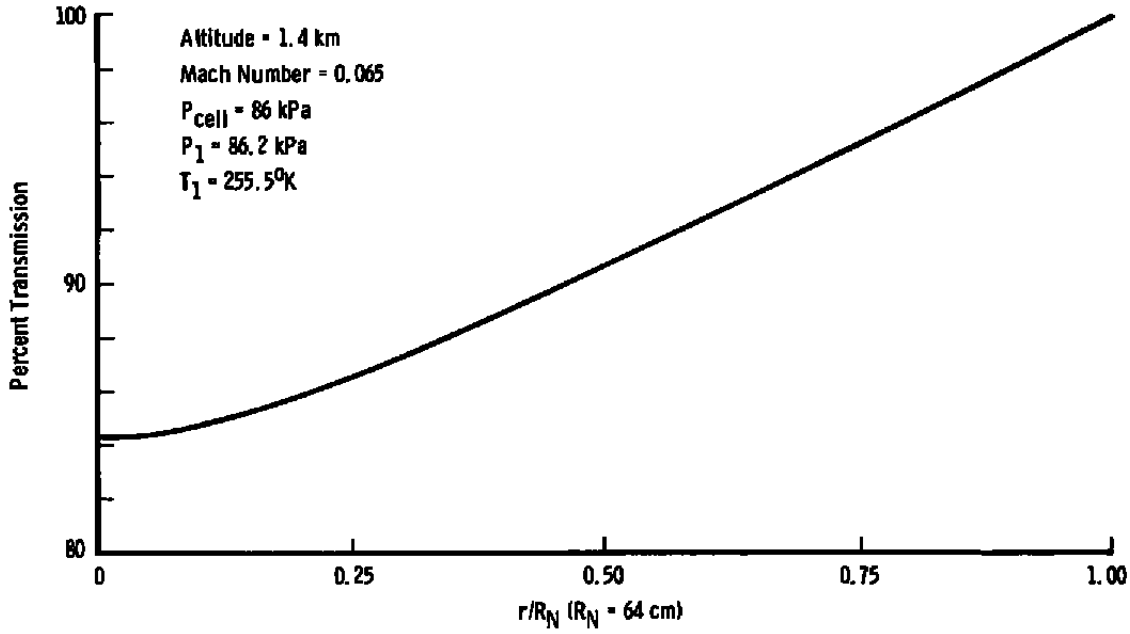

Figure 9. Measured transmission profiles using the second bandhead of the (0,0) γ-band of NO at 10.2 cm downstream of nozzle exit for maximum afterburn power.

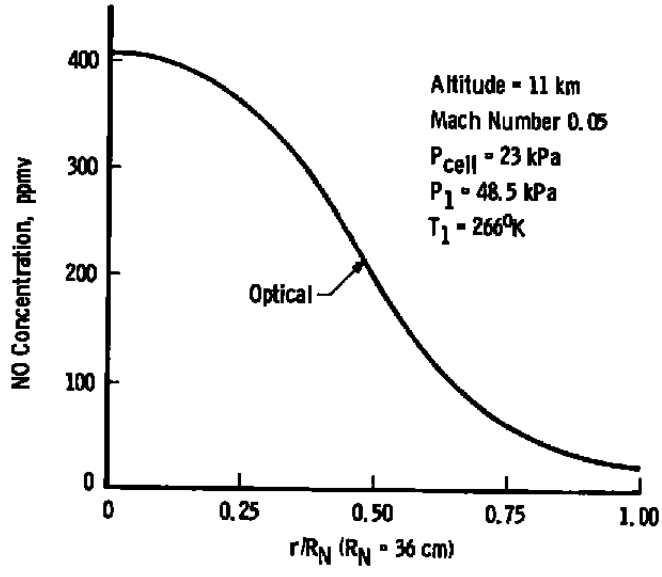

Figure 10. Results of inverting the transmissivity profile to local values of NO concentration at 10.2 cm downstream of nozzle exit for intermediate power.

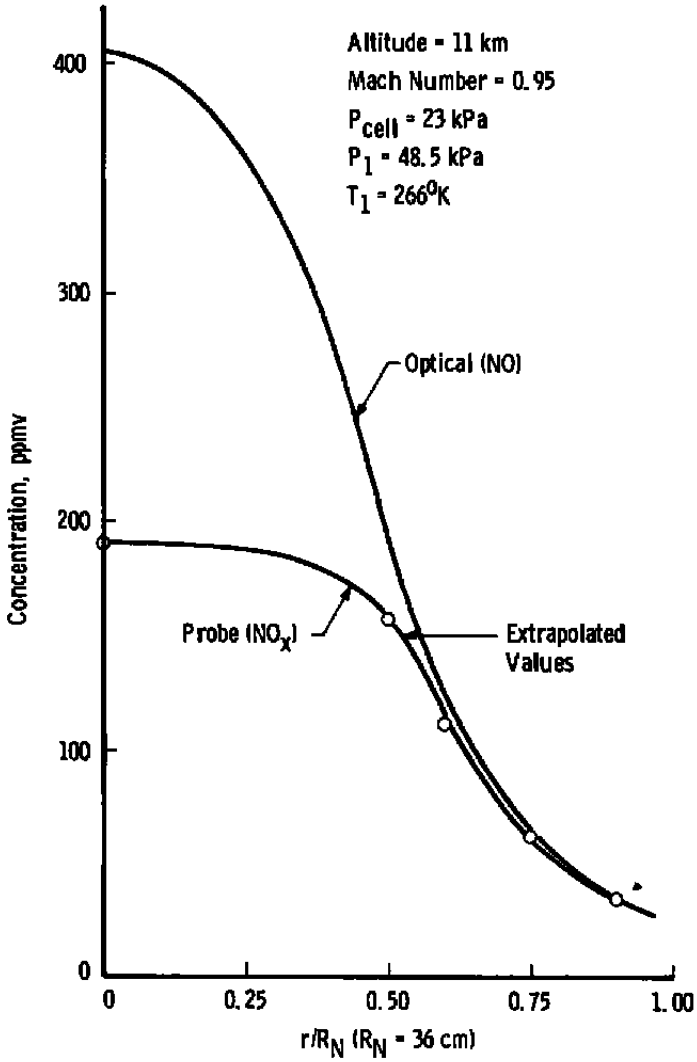

Figure 11. Results of inverting the transmissivity profile to local values of NO concentration compared to to probe-measured values at 10.2 cm downstream of nozzle exit for intermediate power.

The NO concentration profile derived from the optical measurements for the afterburning engine is shown in Fig. 12. There are no probe data available for comparison at this flight condition. The increase in the NO number density over that obtained at the intermediate power setting is to be expected because of the large increase in static temperature of the exhaust stream (compare Figs. 4 and 5). It must be

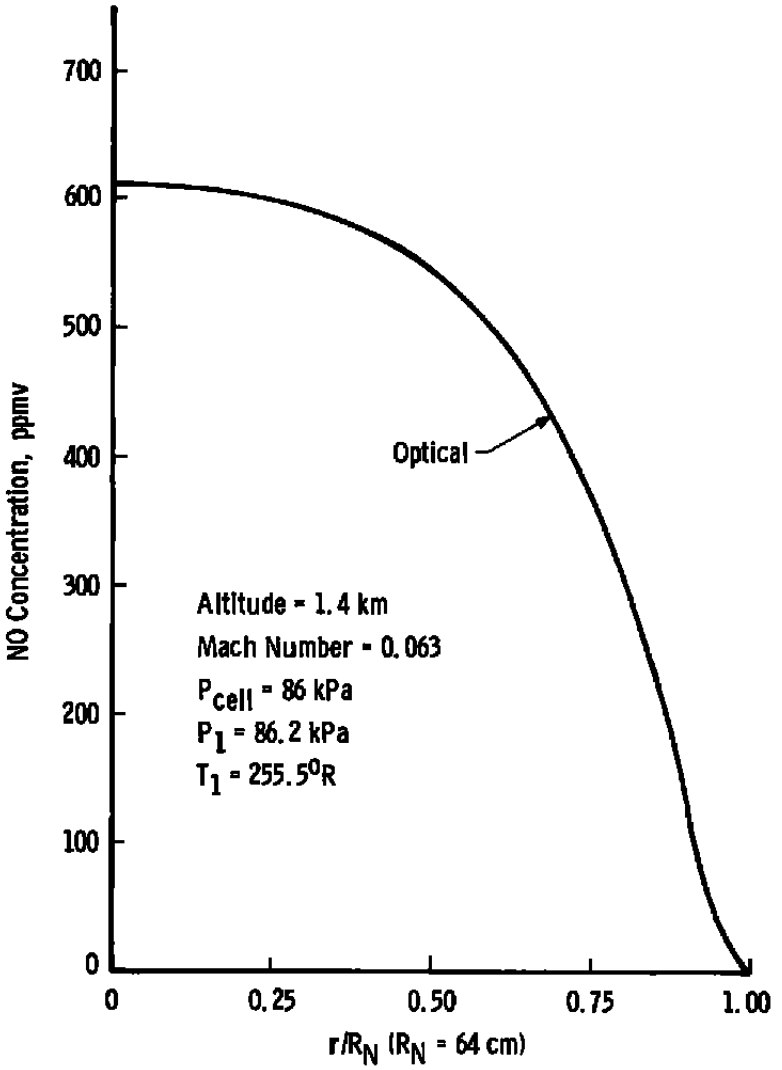

Figure 12. Results of inverting the transmissivity profile to local values of NO concentration at 10.2 cm downstream of nozzle exit for maximum afterburn power.

noted that the afterburning optical measurement was made in the reaction zone of the afterburning exhaust stream near the nozzle exit. The reaction zone continues further downstream from the optical measurement location; therefore, the measured NO concentration may be greater or smaller than the amount of NO finally injected into the atmosphere. Further work is necessary to determine this latter quantity.

4.3 CONTINUUM ABSORPTION DATA (NO_2)

The continuum absorption system was used to acquire the data necessary to ascertain the NO_2 concentration levels in the jet engine exhaust stream. The system was developed and the performance analyzed in the laboratory to serve as a calibration for the engine measurement. When the data taken at an intermediate power setting on the engine were examined, no discernable absorption could be detected. The experiment was not conclusive; however, approximately 20 ppmv of NO_2 would have produced measurable absorption based on the laboratory calibration. This measurement provides strong evidence that the probe-measured NO_x was predominantly NO.

4.4 UNCERTAINTIES

A reliable value of uncertainty can only be placed on the measurement of NO concentration in the case of a homogeneous path of known temperature and pressure. In this case the uncertainty in the broadening parameter (±15 percent) used in the equations (Ref. 6) introduces a maximum uncertainty in the measured concentration of about ±10 percent when the broadening parameter, a', is between 0.5 and 2. The values of a' encountered in most measurements of jet engine gas stream are within these bounds. Further errors, attributable to readability of the charts, electronic noise, drift of the source intensity, and errors in measurement of the transmission, are less than 5 percent, so that a root-mean-square uncertainty no greater than about ±12 percent is estimated. The inversion procedure requires the assumption of constant (homogeneous) properties in concentric zones of the jet engine exhaust, and therefore the results of the inversion cannot be assigned an uncertainty. Although a comprehensive analysis was not made here, experience with the propagation calculation for a similar inversion method has shown that uncertainties are largest near the edge of the stream, where absorption is very small, and near the center of the stream, where errors in calculation accumulate. Based on this experience, with propagation through the

inversion and with the known uncertainty for the homogeneous case, the maximum uncertainty of the concentration values (Figs. 10 and 12) is estimated to be less than ±15 percent.

5.0 SUMMARY OF RESULTS

1. Radial profiles of NO concentration were obtained successfully from measured profiles of the integrated transmission at both intermediate and afterburning power settings on the F101 engine exhaust.

2. The NO concentration determined from the UV resonance line absorption measurements is larger by a factor of 2, at the centerline of the engine exhaust, than values of NO_x determined by probe sampling techniques for the F101 engine exhaust at intermediate power.

3. Comparison of optical and probe measurements suggests a reaction within the probe which is temperature dependent.

4. No discernible absorption could be detected for the measurement of NO_2 concentration at intermediate power setting on the F101 engine; this suggests that the probe-measured NO_x is predominantly NO.

REFERENCES

1. McGregor, W. K., Few, J. D., and Litton, C. D. "Resonance Line Absorption Method for Determining of Nitric Oxide Concentration." AEDC-TR-73-182 (AD771642), December 1973.

2. Davis, M. G., McGregor, W. K., and Few, J. D. "Utilizing the Resonance Line Absorption Technique to Determine the Collisional Broadening Parameters of a Diatomic Molecule: NO γ-Bands as an Example." Journal of Quantitative Spectroscopy and Radiative Transfer, Vol. 16, No. 12, December 1976, pp. 1109-1118.

3. Few, J. D., Bryson, R. J., and McGregor, W. K. "Evaluation of Probe Sampling versus Optical In Situ Measurements of Nitric Oxide Concentrations in a Jet Engine Combustor Exhaust." AEDC-TR-76-180 (ADA034726), January 1977.

4. Bishop, B. M., et al. "Anti-Icing and Component Performance Evaluation of the F101-GE-100 Turbofan Engine (S/N 470011/4)." AEDC-TR-75-162 (ADB007941L).

5. Test Facilities Handbook (Tenth Edition). "Engine Test Facility, Vol. 2." Arnold Engineering Development Center, May 1974.

6. Few, J. D., McGregor, W. K., and Glassman, H. N. "Ultraviolet Spectral Absorption Measurements of Nitric Oxide Concentration in T-56 Combustor Exhaust." AIAA Paper No. 76-109, presented at AIAA 14th Aerospace Sciences Meeting, Washington, D.C., January 26-28, 1976.

7. Benson, R. and Samuelsen, G. S. "Oxides of Nitrogen Transformation while Sampling Combustion Products Containing Carbon Monoxide and Hydrogen." Presented at the 1976 Fall Meeting, Western States Section, Combustion Institute, University of California, San Diego, October 18-20, 1976.

NOMENCLATURE

a'	Broadening parameter
M	Mach number
Pa	Pascal, unit of measurement for pressure; 101.325 kPa = 1 atm = 14.7 psia
P_1	Engine inlet pressure, kPa
P_{cell}	Test cell pressure, kPa
P(r)	Radial static pressure distribution
R_N	Nozzle radius, cm
r	Radial distance from center of plume, cm
T_1	Engine inlet temperature, °K
T(r)	Radial static temperature distribution, °K
$t_{00}(r)$	Measured transmissivity at the second bandhead of the (0,0) band
$t_{22}(r)$	Measured transmissivity at the second bandhead of the (2,2) band
$\tau(r)$	Corrected transmissivity distribution
$\tau(y)$	Measured transmissivity for a particular path length (y)